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Distributed control of large numbers of power system resources

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"Understand, predict and control the behavior of complex adaptive systems"

Workshop: Frontiers in distributed optimization and control of sustainable power systems, NREL, Jan 28, 2016

U.S. DEPARTMENT OF ENERGY

PNNL-SA-115641

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CCSI

Control of Complex Systems Initiative

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The Controls Challenge

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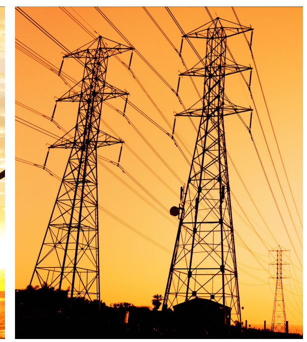
Combining infrastructures, introducing distributed energy resources, and a higher penetration of renewables increases complexity and variability. There is a need for controls that can handle such challenges.



Aug. 2003 blackout:

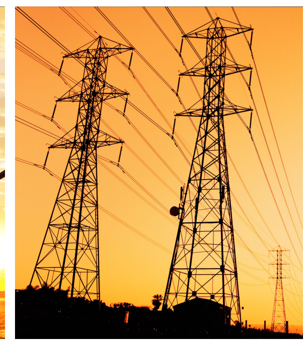
- 50 million customers impacted
- 11 deaths
- cost estimate $4-10 billion

Growing interdependency between buildings and power grid is challenging legacy building controls.

Approach

Flexibility is the key to unleashing the potential of our infrastructures.

Flexibility: By operating assets in our infrastructure differently, we can vary generation and load more while not affecting end users.



CCSI develops control methodologies that take advantage of flexibility in operation.

Controlling flexibility can address complexity and variability.

CCSI: An integrated approach

Theory to underpin system-wide control of large infrastructures
Tools to support implementation and deployment of resulting methodologies
Test bed to validate the approach

Theory

- Divide and conquer approach to ultra-large systems
- Algorithms that are scalable, deployable, robust, resilient, and adoptable

Tools

- Co-simulation
- Visualization
- Validation and verification

Test Bed

- Large-scale simulation
- Hardware-in-the-loop

CCSI leads the way to reliability, efficiency, and sustainability

Advanced controls designed to address complexity and variability allow use of all components of our energy infrastructure to their full potential. The result is a more reliable operation, as well as a more efficient and sustainable use of natural resources.

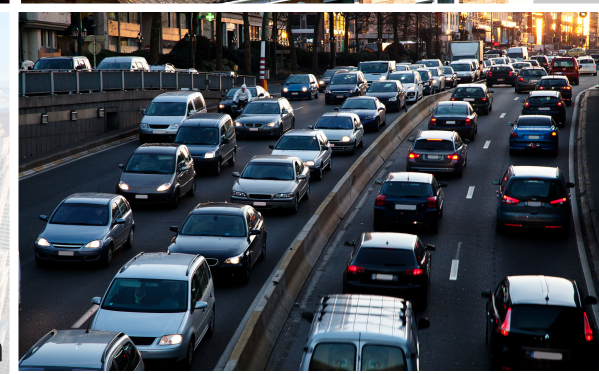




CCSI benefits extend to all infrastructures:

- A more *reliable* electricity system capable of integrating more renewables
- Buildings that consume less energy and contribute to *stability* of the power grid
- Safer and more *sustainable* transportation systems

More *cost-effective* operation of power grid, buildings, and transportation systems



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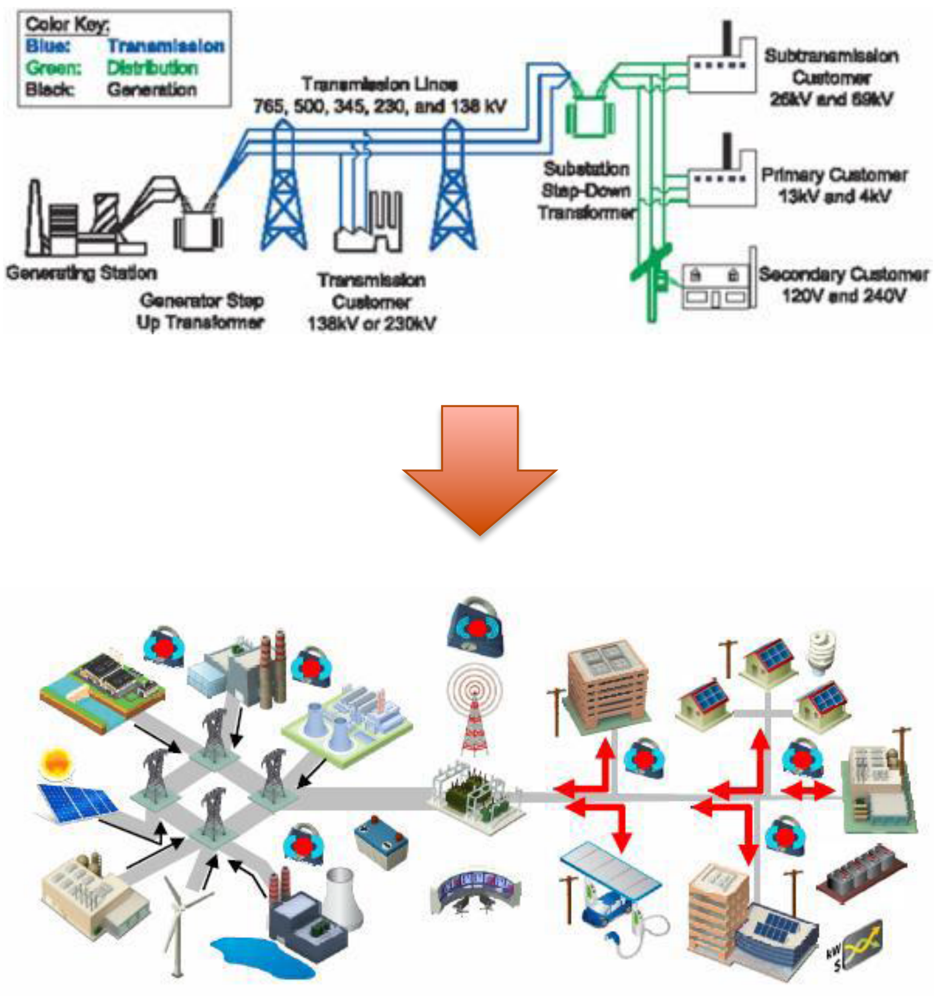
Other Distributed Control Programs @ PNNL

GMLC: Control Theory



Develop new control solutions including topologies, algorithms and deployment strategies for transitioning the power grid to a state where a huge number of distributed energy resources are participating in grid control to enable the grid to operate with lean reserve margins. The theory effort will recognize the need to engage legacy control concepts and systems as we transition to more distributed control.

PoP: FY16/17/18

Budget: $6.5M

Labs: LANL, PNNL, ANL, INL, NREL, SNL, LLNL

Partners: Oncor Electric Delivery, PJM Interconnection LLC, United Technologies Research Center

Virtual Battery-Based Characterization and Control of Flexible Building Loads Using VOLTTRON - Summary

FY16-17-18

$3.6M ($1.25M FY16)

The goal of this project is to understand the capacity to use building loads as virtual storage resources and develop control methods to utilize that capacity for transactive buildings that provide grid services.

1. Understand the capacity of loads such as HVAC, hot water, and refrigeration in commercial and residential buildings to provide virtual storage as a substitute for physical storage on the power grid.
2. Develop algorithms to optimally control building loads to provide grid services and benefit building owners

Partners:

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Oak Ridge National Laboratory

UF University of Florida

NREL National Renewable Energy Laboratory

United Technologies Research Center

TVA

Bonneville Power Administration

BOSCH

Building Technologies Office

Target Market:
The solution is intended for deployment in commercial and residential buildings by energy service providers (e.g. utilities, aggregators) or control system vendors to provide transactive grid services

Multi-scale Incentive-Based Control of Distributed Assets
ARPA-E NODES

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Technology Summary

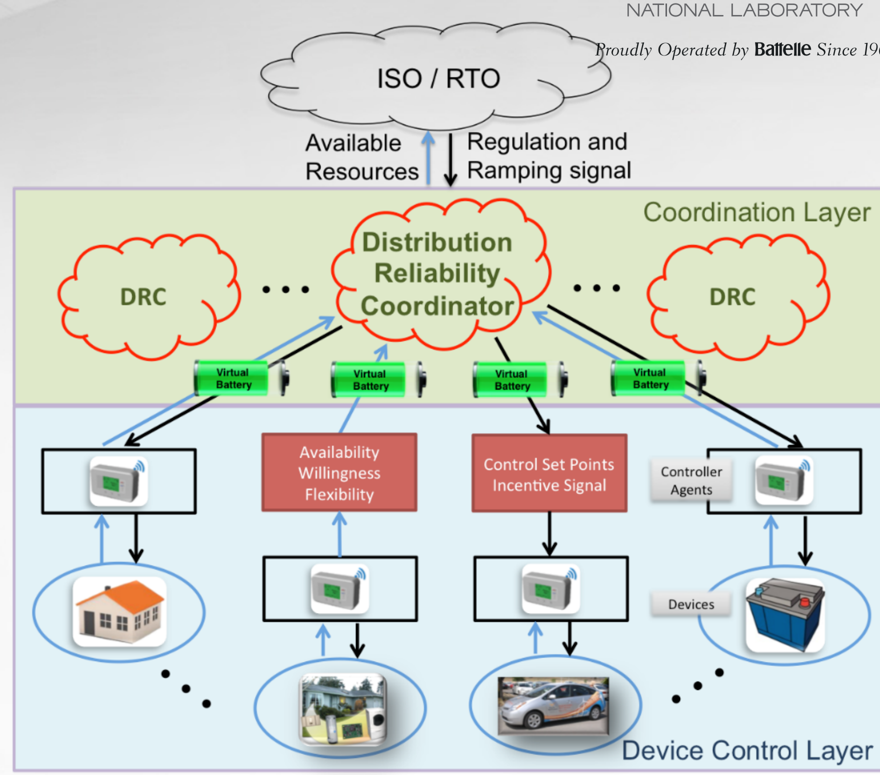
- *Available system flexibility estimated using simple virtual battery models*
- *Incentive mechanisms used to economically and efficiently acquire resources without revealing private information*
- *Engaged resources respond autonomously to self-sensed frequency and global control signal received from system*

Technology Impact

- *Improves efficiency and reliability of grid by engaging lowest cost resources to provide ancillary services*
- *Provides level playing field for distributed assets with conventional generation sources*
- *Reduces need for new transmission lines by providing fast-acting location-dependent resources*

Proposed Technical Category and Target Metrics

Features	Description
Category	*Category 1, 2 and 3*
Managed DERs	*residential and commercial HVAC systems, smart appliances, electric vehicles, thermal energy storage, PV inverters*
FOA Metrics	*Initial Response Time <2 seconds; reserve magnitude target >2% for frequency response, >5% for regulation, and >10% for ramping; availability >95%*



Test Plan

A co-simulation platform will be designed spanning transmission, distribution, ancillary markets, and communication systems. Hardware-in-the loop will incorporate grid-edge control, DER equipment and systems coupled with virtual components in the simulation to address scalability. Incentive and control signals will be sent to the DER controllers of the HIL test systems. The physical responses of the devices are fed back into the simulation serving as feedback from the hardware to inform on the simulation.

Incentive-based control provides stable response from millions of distributed assets

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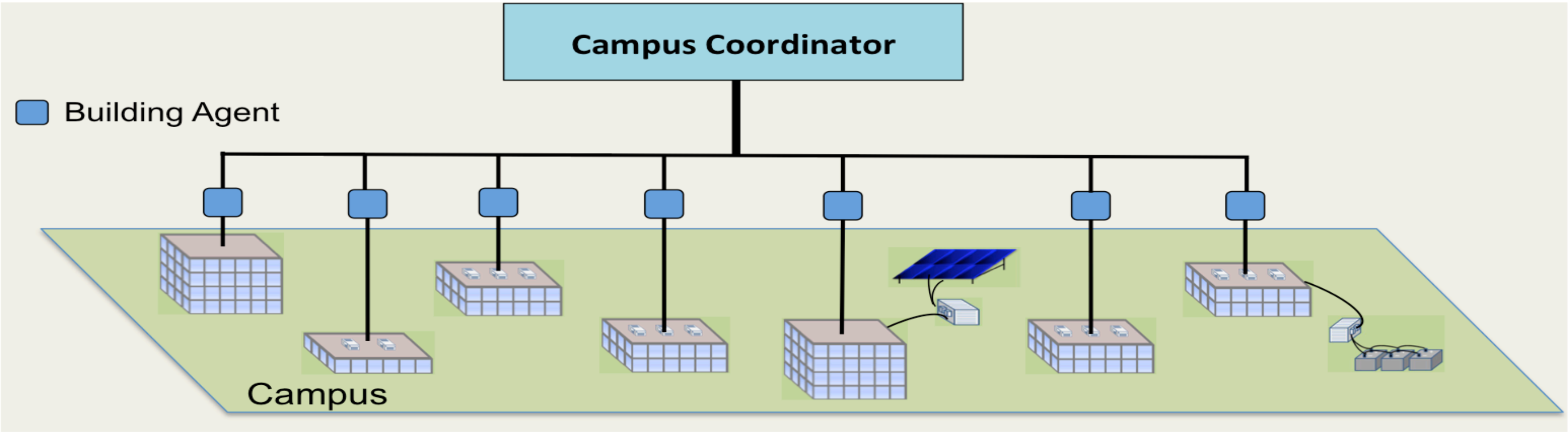
A Distributed Cooperative Power Allocation Method for Campus Buildings

He Hao, Yannan Sun, Thomas E. Carroll, and Abhishek Somani
Power & Energy Society General Meeting, 2015

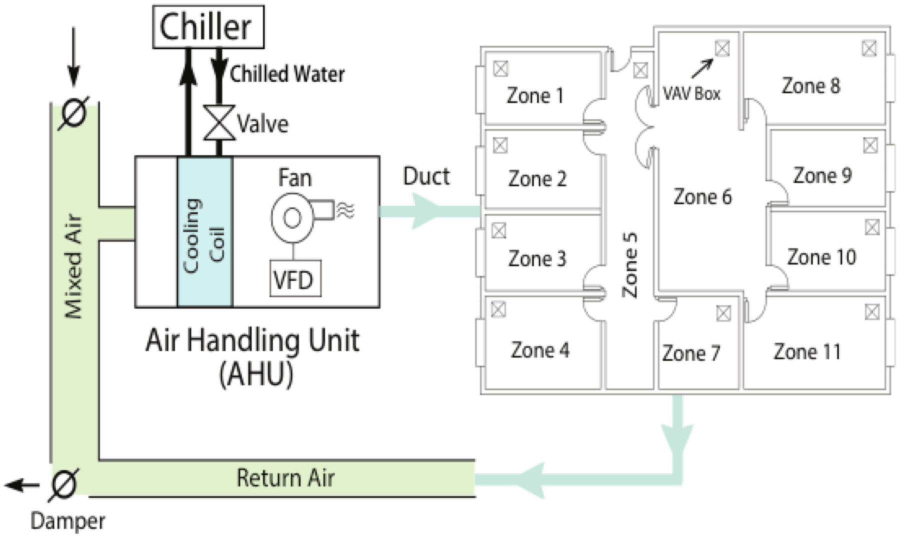
Background

- **5%** peak reduction could reduce the wholesale electricity price by **50%**
- Peak shaving could save **$10–15** billion/year for the U.S. electricity market
- Buildings consume about **40%** of energy and **75%** of electricity in the U.S.
- There are **5.6 million** commercial buildings, contributing **1/3** of peak load
- Peak demand is short, but contributes up to **50%** of the overall building bill

Objective: design a distributed and scalable power allocation method for peak load management and other types of demand modulation for a campus with many buildings.



Model Predictive Control approach to characterize building power flexibility



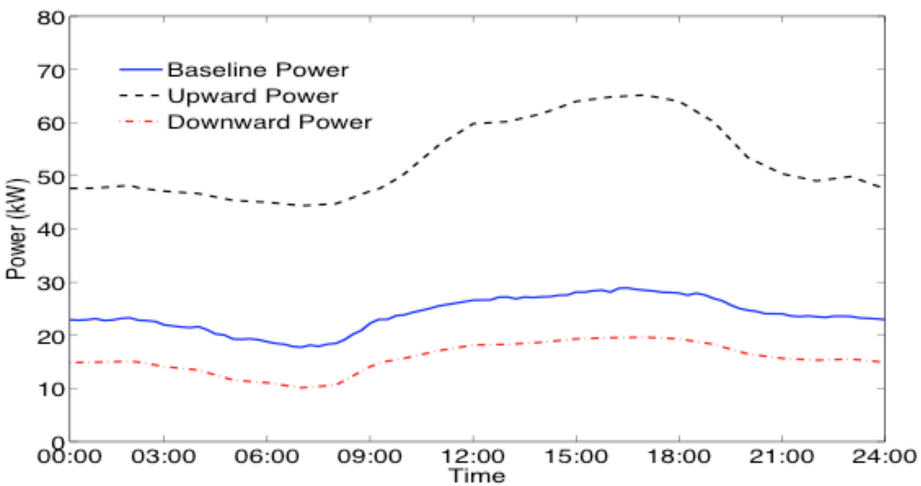
Building thermal dynamics:

$$C_j \frac{dT_j(t)}{dt} = \frac{T_o - T_j(t)}{R_j} + \sum_{k \in \mathcal{N}_j} \frac{T_{(j,k)}(t) - T_j(t)}{R_{(j,k)}} + c_p m_j(t)(T_{s,j}(t) - T_j(t)) + Q_j(t),$$

$$C_{(j,k)} \frac{dT_{(j,k)}(t)}{dt} = \frac{T_j(t) - T_{(j,k)}(t)}{R_{(j,k)}} + \frac{T_k(t) - T_{(j,k)}(t)}{R_{(j,k)}}$$

Building power models:

$$p^f(t) = c_f (m(t))^3 \qquad p^c(t) = \frac{c_p m(t) \Delta T_c(t)}{\eta_c \, COP_c}$$



MPC-based flexibility estimation:

$$\min_{u_{t \to t+N}} \sum_{k=0}^{N-1} w_{t+k} \, p_{t+k}$$

subject to:

$$x_{t+k+1} = f(x_t, u_t, w_t), \quad \forall\, k \in \mathbb{K},$$
$$x_{t+k} \in \mathcal{X}_{t+k}, \; u_{t+k} \in \mathcal{U}_{t+k}, \quad \forall\, k \in \mathbb{K},$$
$$x_{t+N} \in \mathcal{X}_{t+N},$$

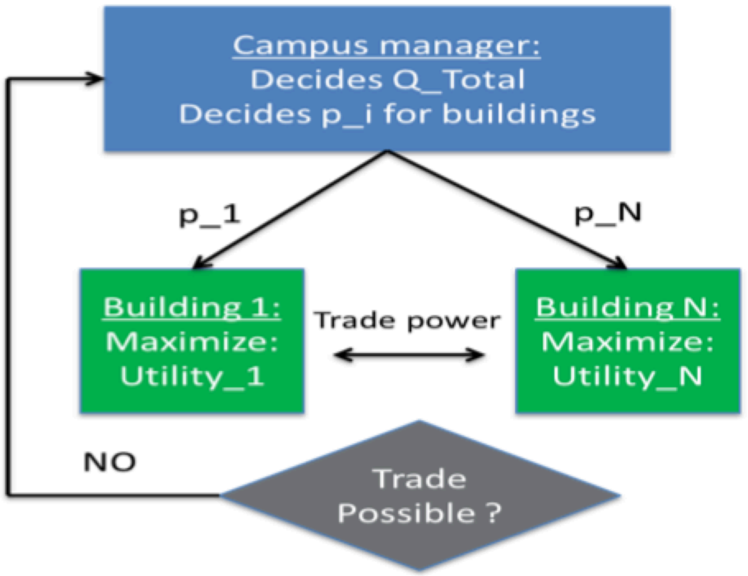
Nash bargaining and dual decomposition are used to solve the negotiation problem

Nash bargaining :

$$\max_{p_i\text{'s}} \quad \prod_{i=1}^{n}(u_i(p_i) - u_i(p_i^d))$$

$$\text{subject to:} \quad \sum_{i=1}^{n} p_i \leq Q,$$

$$p_i^- \leq p_i \leq p_i^+, \quad \forall\, i \in \{1, \cdots, n\}$$



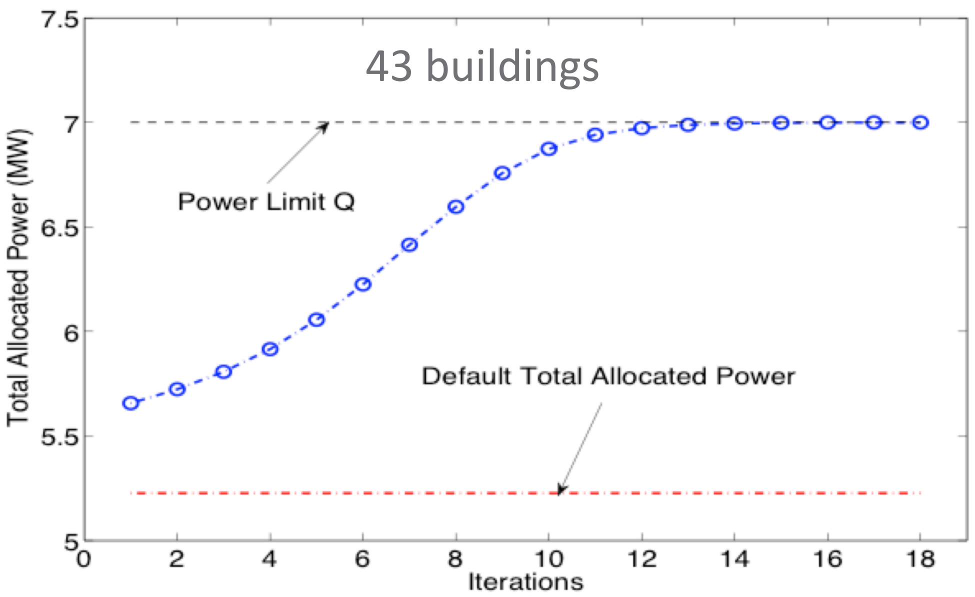
Dual decomposition:

$$\min_{q_i} \quad g_i(q_i) + \lambda\beta_i q_i$$

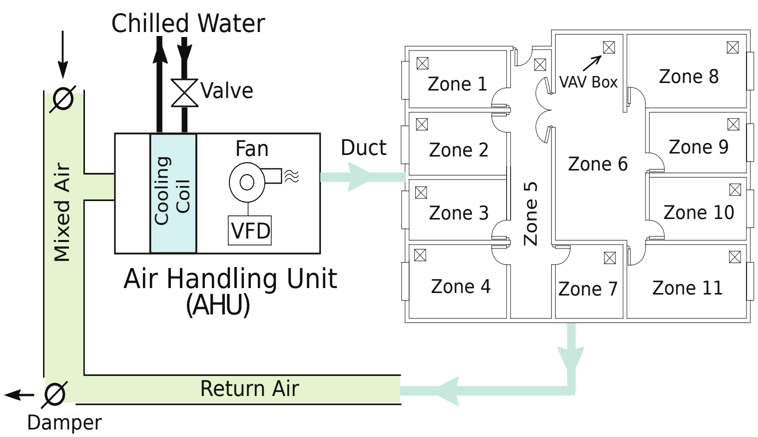
$$\text{subject to:} \quad 0 \leq q_i \leq 1.$$

$$s = Q - \sum_{i=1}^{n}(\beta_i q_i^* + p_i^-)$$

$$\lambda := \max\{\lambda - as, 0\}$$

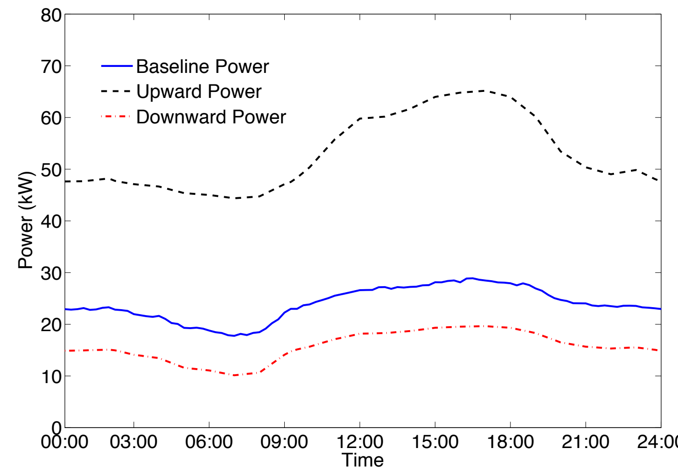


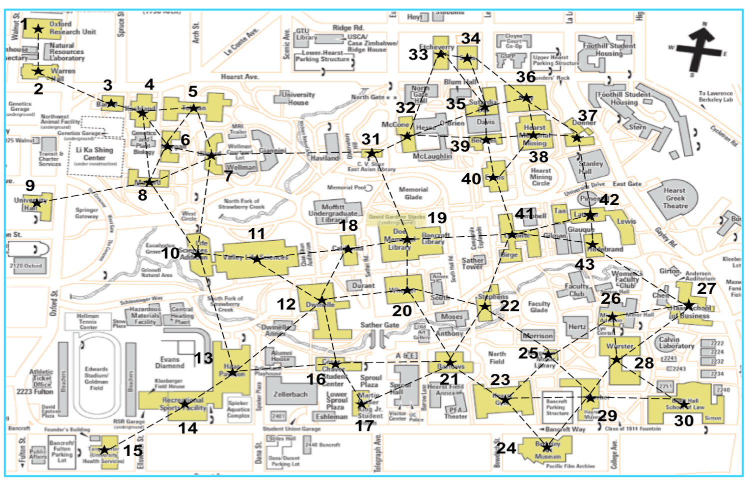
Results



MPC

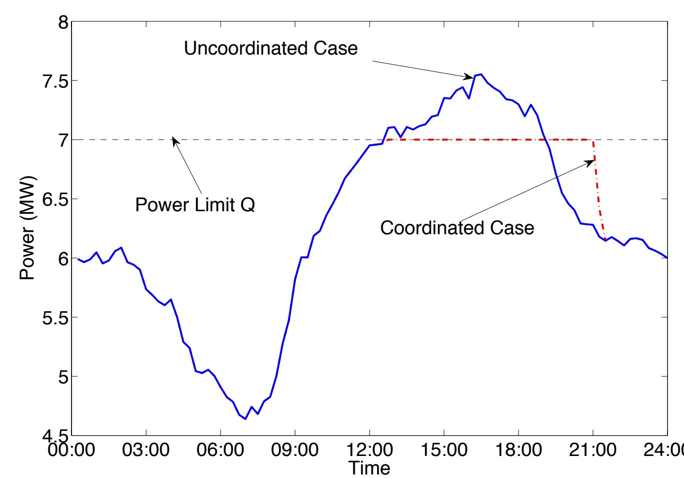
Model Predictive Control





Nash Bargaining

Dual Decomposition



Minimum-time Consensus and its grid applications

T. Yang, D. Wu, Y. Sun and J. Lian, "Minimum-time consensus based approach for problems in a smart grid," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 12, pp. 1318-1328, 2016.

Motivation

- Classical consensus algorithm converges asymptotically
- High communication cost
- Time constraints
- How to reduce the computational time?

Minimum-time Consensus

- Minimum-time consensus
  - Each agent runs classical consensus and stores local states over a few number of time steps
  - Computes the consensus value with local states within a minimum number of time steps even before consensus is achieved with a reasonable accuracy
  - Accelerate the convergence time and alleviate the communication burden
- Grid applications: Load shedding and economic dispatch problem

Minimum-time Consensus

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- Step 1: each agent runs the classical consensus

$$x_j(k+1) = p_{jj}x_j(k) + \sum_{i \in \mathcal{N}_j^+} p_{ji}x_i(k)$$

- Step 2: stores the local states, computes the differences, and constructs a square Hankel matrix

$$\boldsymbol{H}_j^i \triangleq \begin{bmatrix} \overline{x}_j(1) & \overline{x}_j(2) & \dots & \overline{x}_j(i) \\ \overline{x}_j(2) & \overline{x}_j(3) & \dots & \overline{x}_j(i+1) \\ \vdots & \vdots & \ddots & \vdots \\ \overline{x}_j(i) & \overline{x}_j(i+1) & \dots & \overline{x}_j(2i-1) \end{bmatrix}$$

- Step 3: check the rank. If it loses rank, then computes its normalized kernel $\boldsymbol{\beta}^{(j)} = [\beta_1^{(j)}, \dots, \beta_{M_j-1}^{(j)}, 1]^{\mathrm{T}}$
- Step 4: computes the final consensus value

$$\mu = \lim_{k \to \infty} x_j(k) = \frac{\boldsymbol{x}_{M_j}^{\mathrm{T}} \boldsymbol{\beta}^{(j)}}{\boldsymbol{1}^{\mathrm{T}} \boldsymbol{\beta}^{(i)}} \quad \text{where } \boldsymbol{x}_{M_j} = [x_j(0), \dots, x_j(M_j - 1)]^{\mathrm{T}}.$$

Minimum-time Consensus Backup

- Guaranteed to lose rank at time step M_j
- M_j is equal to the degree of a minimal polynomial of the matrix pair (C_j, P)

  where $C_j = \begin{bmatrix} 0 & \dots & 0 & 1_{\text{j-th}} & 0 & \dots & 0 \end{bmatrix}$
- The minimal polynomial of the matrix pair (C_j, P) denoted by $q_j(t) = t^{M_j} + \sum_{i=0}^{M_j-1} \alpha_i^j t^i$ is the monic polynomial of the minimum

  degree M_j that satisfies $C_j q_j(P) = 0$

Application to Distributed Load Shedding

- Recall the ratio consensus based algorithm

$$y_j(k+1) = p_{jj} y_j(k) + \sum_{i \in \mathcal{N}_j^+} p_{ji} y_i(k),$$

$$z_j(k+1) = p_{jj} z_j(k) + \sum_{i \in \mathcal{N}_j^+} p_{ji} z_i(k).$$

- It computes the average asymptotically in the sense that

$$\lim_{k \to \infty} \frac{y_j(k)}{z_j(k)} = \frac{\sum_{i=1}^{n} y_i(0)}{n}.$$

- Apply the minimum-time consensus, each agent computes the average system overload in a minimum number of time steps

Application to EDP

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- Recall the distributed algorithm for EDP

$$\lambda_i(k+1) = p_{i,i}\lambda_i(k) + \sum_{j \in \mathcal{N}_i^+} p_{i,j}\lambda_j(k) + \epsilon y_i(k),$$

$$x_i(k+1) = \phi(\beta_i \lambda_i(k+1) + \alpha_i),$$

$$y_i(k+1) = q_{i,i}y_i(k) + \sum_{j \in \mathcal{N}_i^+} q_{i,j}y_j(k) - (x_i(k+1) - x_i(k)).$$

- It solves the EDP asymptotically
- Apply the minimum-time consensus, EDP is solved in a minimum number of time steps

Case studies

- Directed communication network

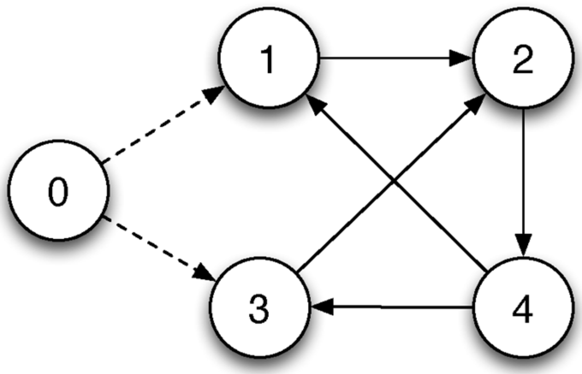
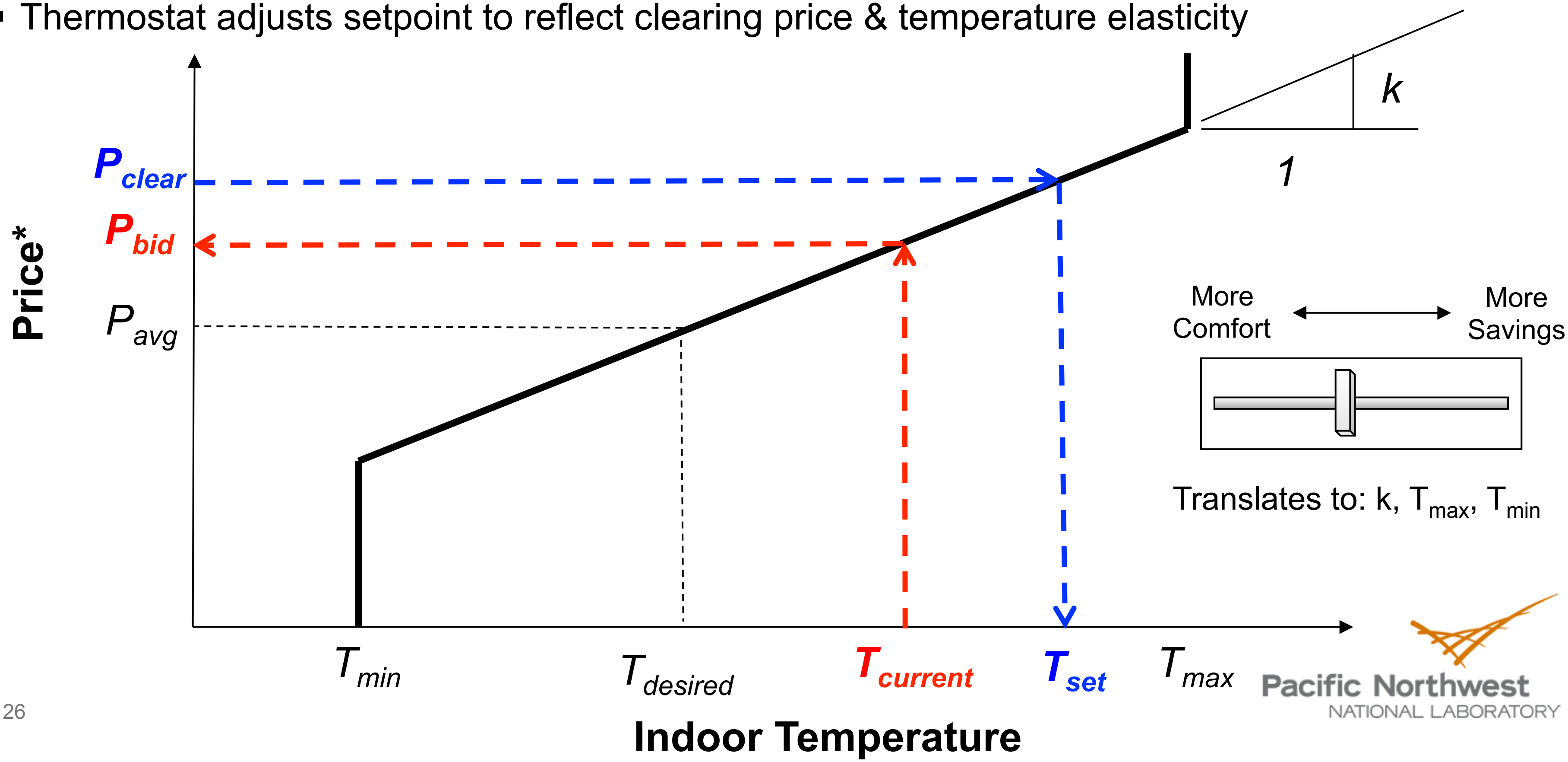


Figure: Communication topology

Transactive Control & Coordination: A Double-Auction Based Approach to Distributed Control and Decision-making

Transactive Cooling Thermostat Generates Demand Bid based on Customer Settings

- User's *comfort/savings* setting implies limits around normal setpoint ($T_{desired}$), *temp. elasticity* (*k*)
- Current temperature used to generate bid price at which AC will "run"
- AMI history can be used to estimate bid quantity (AC power)
- Market sorts bids & quantities into demand curve, clears market returns clearing price
- Thermostat adjusts setpoint to reflect clearing price & temperature elasticity



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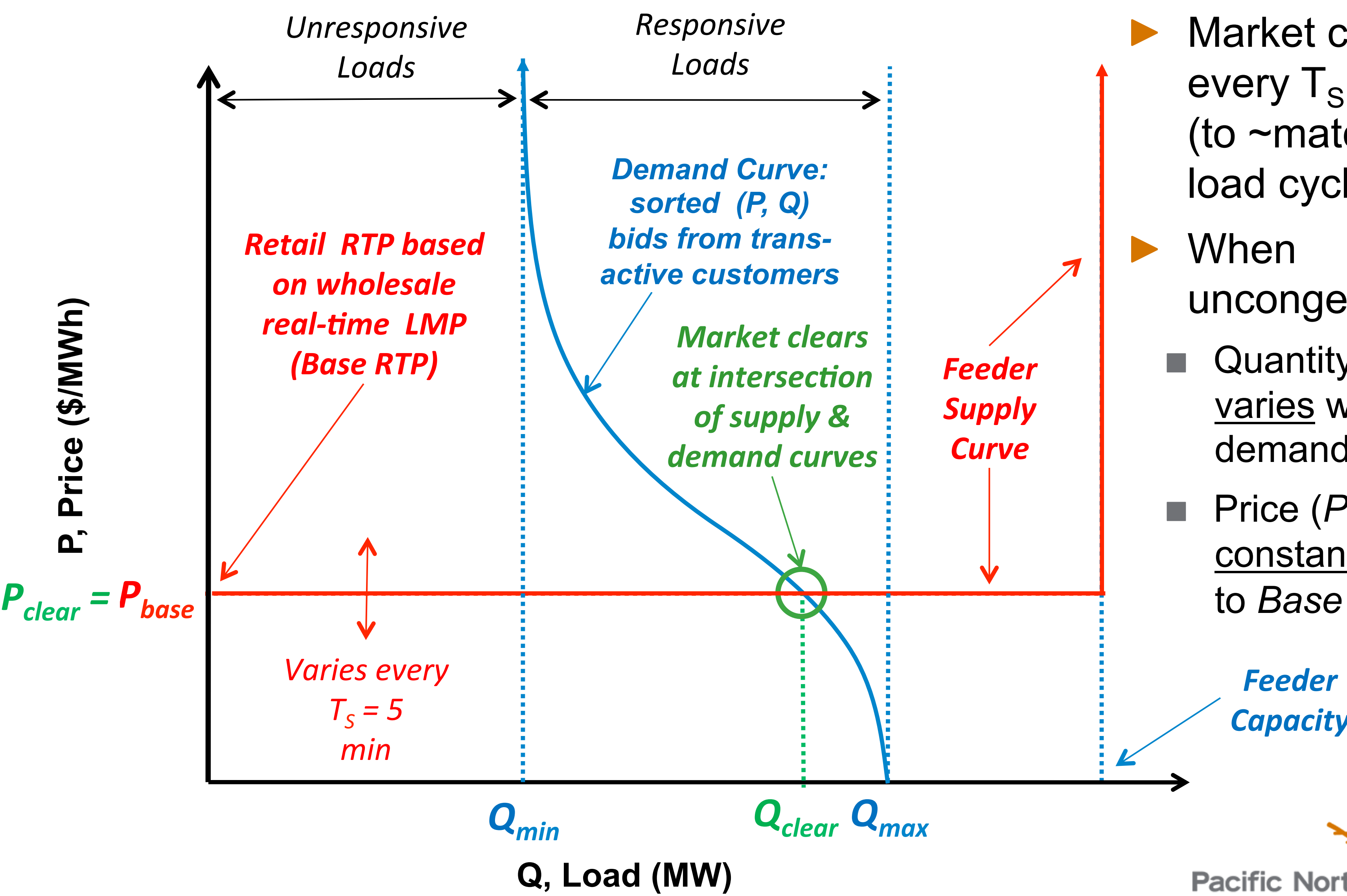
RTP Double Auction Market – *Uncongested*



- Market clears every T_S= 5min (to ~match AC load cycle)
- When uncongested:
  - Quantity (Q_{clear}) <u>varies</u> with demand curve
  - Price (P_{clear}) is <u>constant</u>, equal to *Base RTP*

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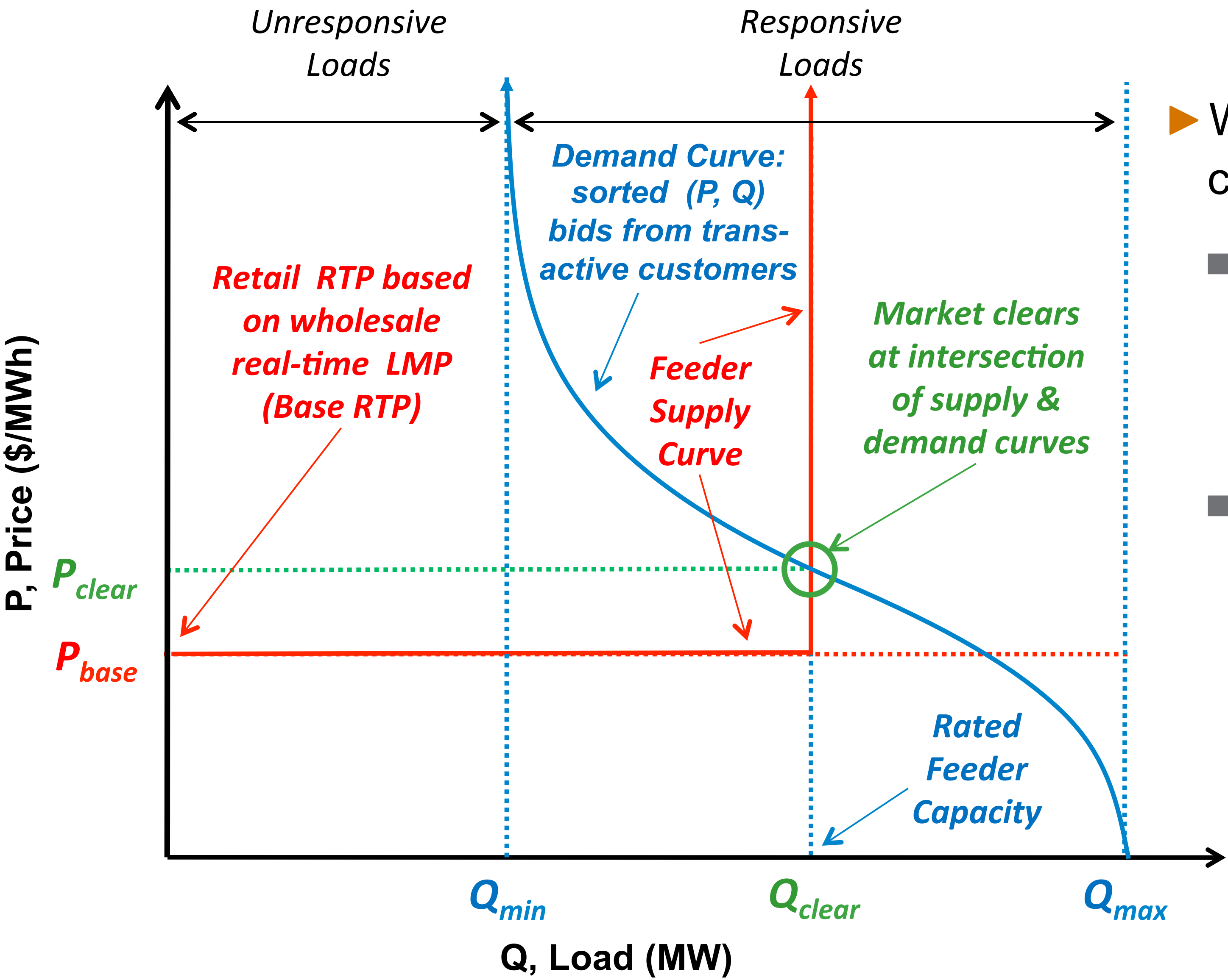
RTP Double Auction Market – *Congested*



- When constrained:
  - Quantity (Q_{clear}) is <u>constant</u> at rated feeder capacity
  - Price (P_{clear}) <u>varies</u> to keep load at rated capacity

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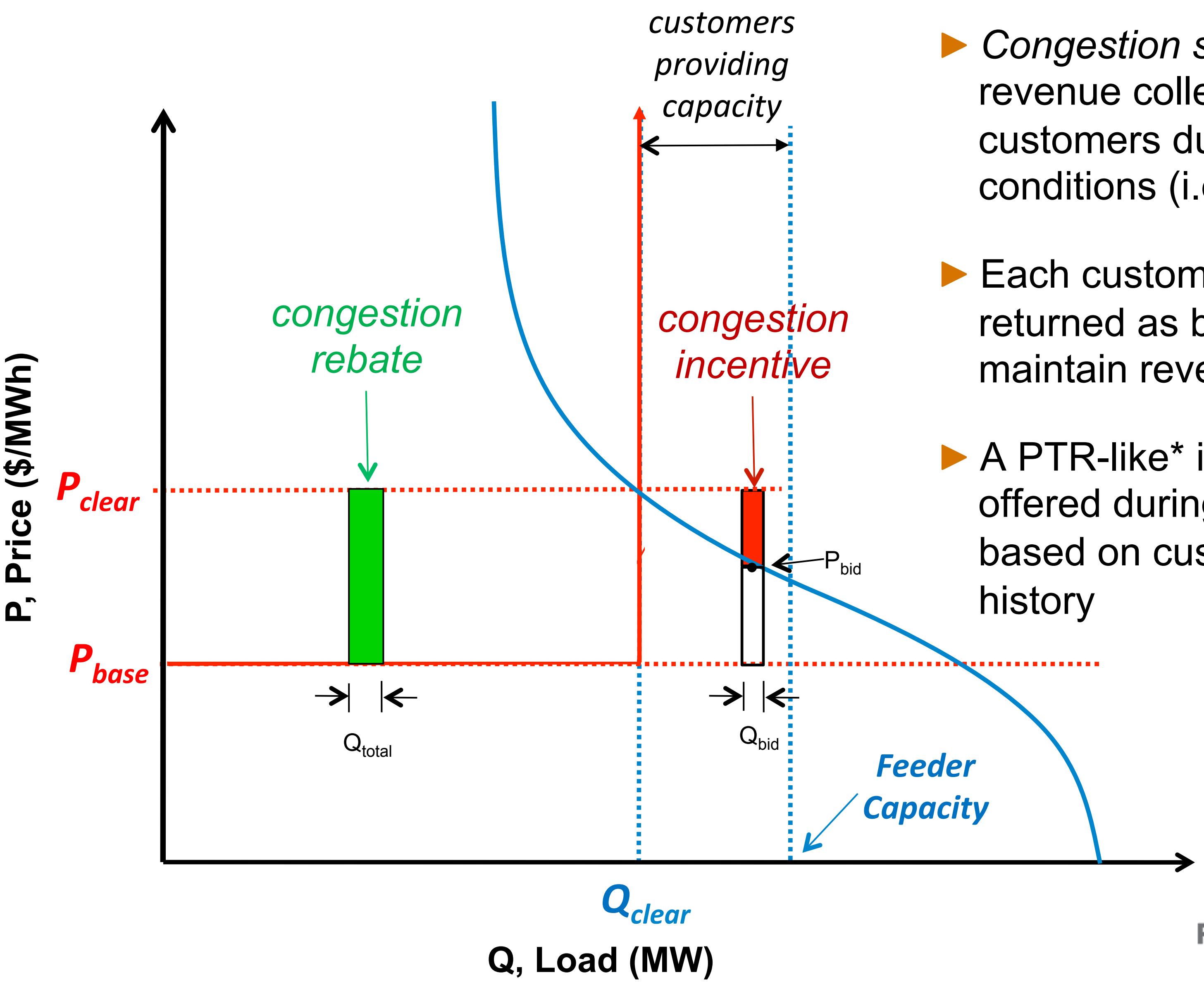
What about the Congestion Surplus?

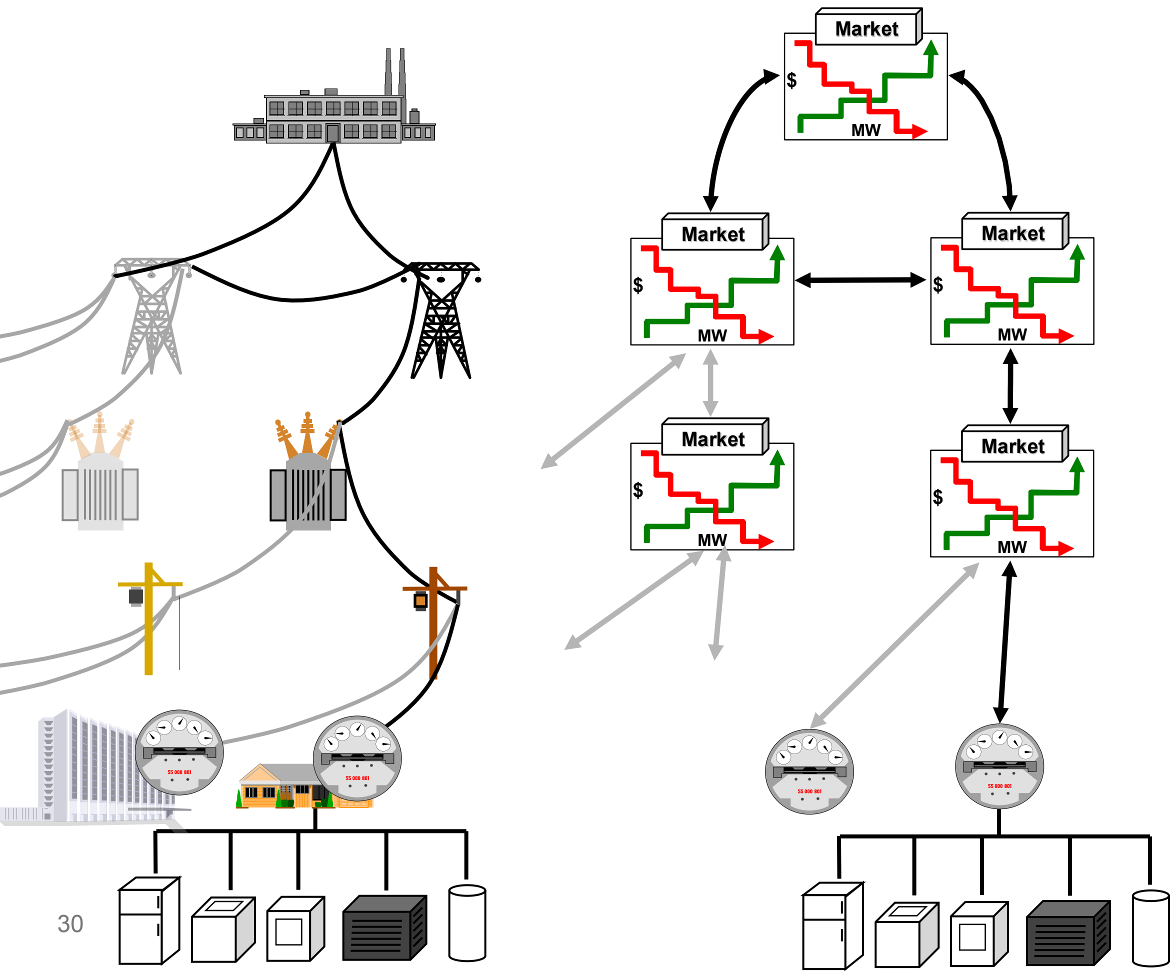


- *Congestion surplus* is <u>extra</u> revenue collected from customers during constrained conditions (i.e. $P_{clear} > P_{base}$)
- Each customer's surplus returned as billing rebate to maintain revenue neutrality
- A PTR-like* incentive is also offered during congestion, based on customer's bid history

* peak time rebate

Hierarchical Network of Transactive Nodes Parallels the Grid Infrastructure

Node: point in the grid where flow of power needs to be managed



Node Functionality:

- "Contract" for power it needs from the nodes supplying it
- "Offer" power to the nodes it supplies
- Resolve price (or cost) & quantity through a price discovery process
  - market clearing, for example
- Implement internal price-responsive controls

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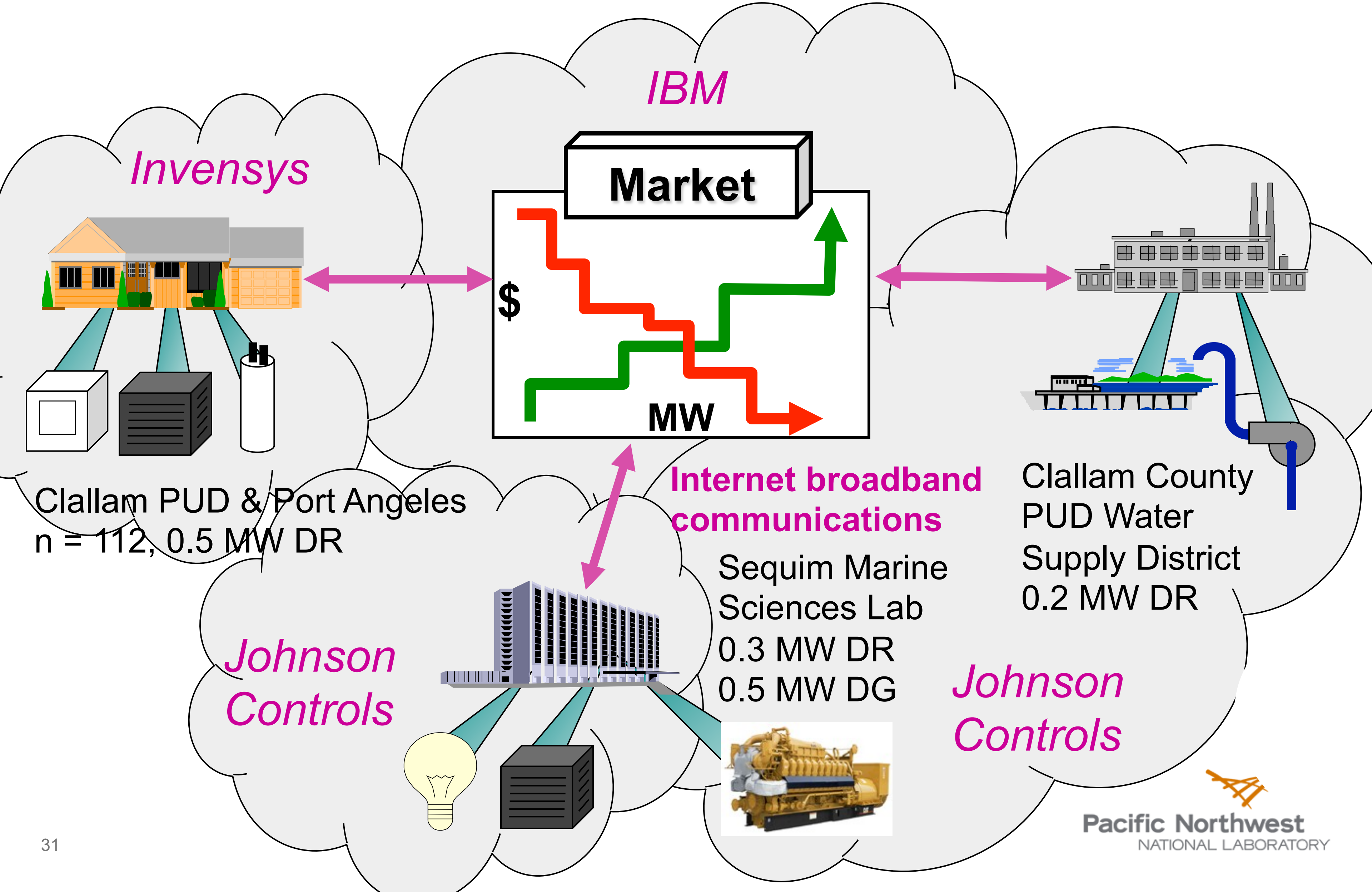
Olympic Peninsula Demonstration



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Pacific Northwest Demonstration Project

What:

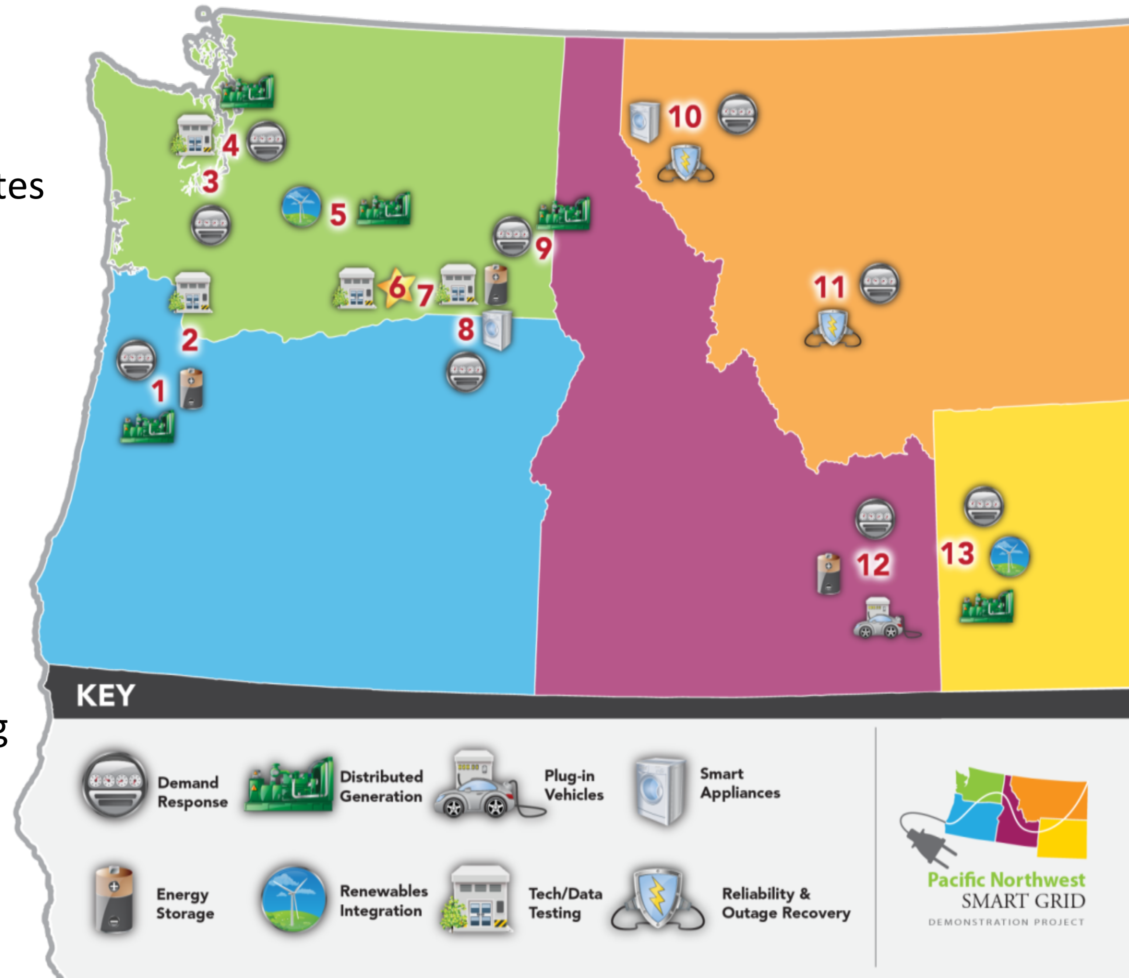
- $178M, ARRA-funded, 5-year demonstration
- 60,000 metered customers in 5 states

Why:

- Quantify costs and benefits
- Develop communications protocol
- Develop standards
- Facilitate integration of wind and other renewables

Who:

Led by Battelle and partners including BPA, 11 utilities, 2 universities, and 5 vendors



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Thank you for your attention.

Any questions?